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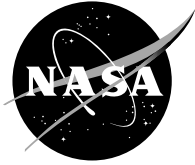
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TESTING AND ANALYSIS OF NEXT ION ENGINE DISCHARGE CATHODE ASSEMBLY WEAR

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ABSTRACT

Experimental and analytical investigations were conducted to predict the wear of the discharge cathode keeper in the NASA Evolutionary Xenon Thruster. The ion current to the keeper was found to be highly dependent upon the beam current, and the average beam current density was nearly identical to that of the NSTAR thruster for comparable beam current density. The ion current distribution was highly peaked toward the keeper orifice. A deterministic wear assessment predicted keeper orifice erosion to the same diameter as the cathode tube after processing 375-kg of xenon. A rough estimate of discharge cathode assembly life limit due to sputtering indicated that the current design exceeds the qualification goal of 405-kg. Probabilistic wear analysis showed that the plasma potential and the sputter yield contributed most to the uncertainty in the wear assessment. It was recommended that fundamental experimental and modeling efforts focus on accurately describing the plasma potential and the sputtering yield.

NOMENCLATURE

e	elementary charge, 1.6×10^{-19} C
E	energy, eV
f	yield constant, atoms/ion-eV ²
f(x)	distribution function
j	current density, A/cm ²
J	current, A
k	Boltzmann's constant, 1.6×10^{-19} J/eV
M	atomic or ionic mass, kg
N	number of particles
n	number density, m ⁻³
R	ratio of double-to-single ion current
T	temperature, eV
\dot{V}	volumetric erosion rate, m ³ /s
Y(E)	ion energy dependent sputter yield, atoms/ion
Y _{eff}	effective sputter yield
λ_Y	stochastic yield factor
μ	mean value for distribution function
π	3.141592
ρ	mass density, kg/m ³
σ	standard deviation

Subscripts

A	Avogadro's, 6.022×10^{26} atoms/kmol
e	electron
i	ion or index
k	keeper

Superscripts

+	singly charged ions
++	doubly charged ions

INTRODUCTION

Ion propulsion systems are currently deployed on at least 17 active spacecraft performing stationkeeping and primary propulsion duties.¹ The recently concluded Deep Space 1 mission demonstrated the maturity of ion engine technology for primary planetary propulsion applications and led to its selection for the DAWN mission to orbit the asteroids 4 Vesta and 1 Ceres.² The DAWN mission requires three ion engines to process a total of 288-kg of xenon, 2.4 times the flight qualified throughput of the NASA Solar Electric Propulsion Technology and Applications Readiness (NSTAR) engine.^{2,3} NASA's Evolutionary Xenon Thruster (NEXT) is currently under development for use in a

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solar electric propulsion stage capable of delivering flagship class spacecraft to the outer planets and for sample return missions.⁴ The variance in the erosion of the discharge cathode keeper in ground tests of the NSTAR engine has been demonstrated to be relatively large and possibly a nonlinear function of throttling condition.^{5,6} This investigation seeks to shed new light on the processes governing and limiting prediction accuracy of discharge cathode keeper wear in the NEXT engine through a combination of experimental and analytical techniques.

During the NSTAR development program, three wear tests were performed on the 30-cm engine, and the Extended Life Test (ELT) was the ground test of the flight spare Deep Space 1 (DS1) ion engine. The first wear test revealed unacceptably high erosion of the discharge cathode assembly,⁷ and the engineering solution was to use a sacrificial keeper maintained at a potential intermediate between the discharge cathode and anode. The subsequent 1,000 hour wear test validated the approach to mitigate discharge cathode wear.⁸ An 8,200 hour wear test was conducted on an engineering model NSTAR thruster, and the discharge cathode keeper wear was consistent with the results of the 1,000 hour test.^{5,9} Photographic data taken of the ELT revealed that the discharge keeper orifice diameter was increasing after approximately 4,600 hours of operation.^{5,6} While neither of the previous wear tests experienced growth in the discharge keeper orifice diameter, growth would be expected if extending the operation to high throughput. Nevertheless, the orifice diameter growth was observed within the same period of the 8,200 hour test. Through a relatively simple analysis, it was shown that the wear observed in the ELT could be considered consistent with the 8,200 hour test within the bounds of uncertainty of the ion flux, energy and spatial distributions, and sputter yield.⁵ The present investigation seeks to predict the wear of the NEXT discharge cathode keeper and to quantify the accuracy of the prediction.

A series of experiments were devised and conducted to measure both the ion current and its spatial distribution to the discharge cathode keeper of a NEXT 40-cm engine. The results are presented and discussed. The discharge cathode keeper ion current was also used to make predictions of the erosion of the keeper. A probabilistic wear analysis was developed to assess both the accuracy to which the keeper wear can be predicted and which parameters contribute most to the uncertainty. The analysis is presented along with suggested improvements.

TEST HARDWARE AND PROCEDURES

The NEXT 40-cm ion engine is an evolutionary step from the 30-cm NSTAR and DS1 engines. The NEXT engine is designed to process 7-kW, although de-rating considerations currently limit its maximum power to 6-kW. The most significant departure from its NSTAR heritage is the 1800-V maximum beam voltage (1179-V for NSTAR), and the increased optics area along with the elevated electric field have stressed the optics design. Additionally, the discharge cathode has been scaled to provide the extra current required to drive the ion production. Most of the discharge cathode assembly dimensions have increased to accommodate the elevated current, and some other modifications have been implemented, primarily for ease of manufacturing and structural integrity.

In order to measure the keeper ion current, the discharge cathode keeper was biased below cathode potential. A bias of 20-V was found to be sufficient to achieve ion saturation. The engine is typically operated for at least one hour in discharge only mode for heating. Ion current measurements are taken only after the engine has run with beam extraction for at least one hour. At each throttling condition, the engine is operated for at least one half hour prior to measurement of the keeper ion current. All of these time increments are included to settle the discharge current and to minimize the effects of any thermal transients. Thermal transients were not quantified in this investigation, although qualitative data suggest that they were negligible after one half hour at a fixed beam current.

The ion current distribution to the keeper was measured by increasing the keeper orifice diameter in subsequent tests. Due to time and resource constraints, testing was limited to three diameters beyond the nominal. The two intermediate diameters were chosen because previous experiments⁵ with an NSTAR engine indicated that a proportionally large fraction of the ion current was collected within approximately 2-mm radially of the nominal keeper orifice. The configuration with the keeper tube only was tested so that the ion current collected by the tube could be subtracted from the results when only considering erosion of the keeper orifice plate.

This approach to measuring the ion current collected by the keeper makes two key assumptions: 1. the effect on the surrounding plasma of biasing the keeper significantly negative of cathode is negligible, and 2. the change of keeper geometry has a negligible effect on the local plasma and the ion current collected. The current collected by the probe is small compared to the

discharge (<2 percent) and beam (<7 percent) currents. This suggests that the keeper bias does not significantly alter the overall plasma. While it is recognized that the altered geometry and potential structure likely affect the local plasma properties, quantification of the effects is beyond the scope of the current work, and the results neglect plasma property modifications.

RESULTS

The keeper ion current for NSTAR and the various NEXT geometries is plotted in Figure 1. The results show the strongly linear relationship between beam current and keeper ion current. The linearity suggests that ion currents are largely a function of the overall ion production within the discharge chamber. The total plasma production is more strongly a function of the beam current than of the discharge current. The discharge current is adjusted to maintain the beam current, regardless of the cathode and main flows. The keeper ion current decreases faster than the reduction in surface area as the orifice is enlarged for the NEXT DCA. This result indicates that the local plasma production near the cathode has a strong effect on the total keeper ion current. The average ion current density for both the NSTAR and NEXT engines is depicted in Figure 2. The similarity between NSTAR and NEXT is expected because both engines operate with nearly the same average beam current, and hence nearly the same Bohm current density. As expected from plasma considerations, both Figure 1 and Figure 2 indicate that the total ion flux to ion thruster DCAs is predominantly a function of the beam current for engines comparable in size to NSTAR and NEXT.

For the NEXT engine, two cases were run with the keeper tube without an orifice plate. In the first case, the keeper tube was installed after removal of the orifice plate. Consequently, the inner surface of the keeper was able to collect ions, and the case represented a highly worn condition. The inner surface of the keeper was observed to collect approximately 10 percent of the total ion current of a new keeper. In the second case, a boron nitride sleeve was installed on the tube inner diameter to prevent ion collection on the inner surface. This case was used to calculate the ion current density distribution on the keeper orifice plate. The distribution of the ion current as a function of radius is depicted in Figure 3. The calculation in Figure 3 assumes that all the ion current to the keeper orifice plate is collected on the downstream face; the cylindrical inner diameter of the keeper is neglected. The ion current density is highly peaked toward the inner diameter of the keeper orifice plate. Assuming that the energy of the ions bombarding the keeper is

independent of position, the rate at which the keeper orifice enlarges is expected to be high when the wear is first observed relative to the wear rate as the keeper orifice diameter approaches the cathode tube diameter. In fact the large radial gradient in number density near the cathode orifice likely yields significant radial ambipolar diffusion, and the ion energy and velocity will be a function of radius.^{10,11} Experimental evidence of the radial variation of ion energies near the cathode in the NEXT engine is currently lacking, and the analysis assumes that the energy is independent of radius.

ANALYSIS

The analysis presented in this report focuses on predicting the sputter erosion of the discharge cathode keeper in the NEXT ion engine. The wear prediction is subset of a comprehensive life assessment. As is evidenced by the ELT, erosion of the keeper fails to constitute an end of life condition. Erosion of the keeper is a step along the way toward two possible failure modes: 1. erosion of the cathode orifice plate to tube weld, removing the orifice plate or 2. erosion of the cathode heater causing it to fail, thereby losing restart capability. Both of these modes require development of models more sophisticated than that described here. The wear assessment may be sufficient provided the keeper prevents subsequent erosion during the qualification life of the thruster.

A previous analysis of the erosion observed in the ELT of the DCA on the 30-cm NSTAR engine made a series of simplifying assumptions,⁵ and a goal of the present investigation was to reduce the set of simplifying assumptions. Specifically, the previous investigation assumed a cold ion beam with doubly charged ions was fully responsible for the keeper erosion. This analysis is repeated here for the NEXT DCA with the addition of a radial variation in ion current density across the face of the keeper. Following the simplified deterministic analysis, a more sophisticated approach was implemented in which a Maxwellian ion population was assumed, and the sputter yield was allowed in principle to be a function of both ion energy and incident angle. Additionally, the parameters that affect erosion were varied to assess the contribution that uncertainties in these quantities make toward the overall uncertainty in the wear prediction. The analysis was used to evaluate the NEXT 40-cm discharge keeper wear and some of the limitations of this approach are reported.

Deterministic Wear Prediction

The deterministic wear predictions for the NEXT discharge keeper were based on the analysis reported by Domonkos, *et al.*⁵ This approach assumed that a cold beam of doubly charged ions accelerated through the plasma potential with respect to the keeper was solely responsible for the erosion. The volumetric erosion rate for this set of assumptions is described by Equation 1.

$$\dot{V} = \frac{J_k}{2e} \left[\frac{R}{R+1} \right] Y(E) \lambda_y \frac{M N_A}{\rho} \quad (1)$$

A power law curve fit of the current density on the keeper as a function of radius and beam current (Figure 3) was combined with Equation 1 to predict the time or throughput at which the keeper orifice would be a given radius. Additionally, the yield equation was taken to be of the form recommended by Mantieniks.¹²

$$Y(E) = f(E - E_{th})^2 \quad (2)$$

More sophisticated models exist for the sputter yield near threshold, however the spread in experimental data argues against adoption of a particular model on the grounds of physical accuracy. The model recommended by Mantieniks matches the measured erosion at 100-eV ($Y(100\text{-eV})$) and uses the experimentally determined sputter threshold.¹² This formula simplifies the inclusion of the uncertainty in both the sputtering magnitude and threshold. Finally, the stochastic yield factor is set equal to one in all the calculations presented in this investigation.

The beam current of 3.1-A is the maximum beam current currently in the NEXT throttling table. Although the beam current and keeper ion current are covariant with the plasma density, from the design perspective, the beam current sets the keeper ion current and thus has a first order effect on the lifetime. Since the mass flow rate scales with the beam current, the throughput capability is independent of the beam current, neglecting changes in the ion energy distribution. The ratio of double-to-single ion current is set to 0.176, the NSTAR nominal maximum. Given that this parameter is typically measured far downstream of the thruster, it is considered one of the more poorly quantified parameters governing erosion. The plasma potential was set to 25-V and 30-V with respect to the keeper for the nominal and “worst case” calculations, respectively. The plasma potential being a few volts above the discharge voltage was taken from the data reported by Beattie and Matossian.¹³ This results in a conservative calculation, especially in light of the data reported by Foster and Patterson¹⁰ indicating

that plasma potential under conditions similar to NEXT is less than the discharge voltage. The sputtering threshold voltage of 27-V was taken from Stuart and Wehner¹⁴ for the nominal case. The sputtering threshold of 24-V for the “worst case” calculation was taken from lowest threshold reported for sputtering of molybdenum by Stuart and Wehner.¹⁴ Finally, the sputtering yield at 100-eV was set to 0.06 atoms/ion for both cases.¹⁵ The uncertainty in these parameters is discussed below.

The keeper radius as a function of time and throughput for the cases described in Table 1 is depicted in Figure 4. The results indicate that even in the “worst case” deterministic calculation the engine will process approximately 375-kg of propellant before the discharge cathode keeper orifice has eroded to the same diameter as the cathode tube. In the ELT, this condition was met prior to 12,342 hours, or after processing approximately 100-kg. The engine discharge continued to perform nominally until its voluntary termination earlier this year after 28,436 hours and approximately 225-kg of throughput. The experience of the NSTAR ELT enables a rough estimate of the NEXT DCA life limit due to sputtering to be made. The DCA is expected to last until at least 225 percent of the time required for keeper orifice plate erosion to the cathode diameter; for the “worst case” assumptions for NEXT, the DCA life is expected to be at least 844-kg. Hence, the qualification goal of 405-kg for NEXT appears to be well within the reach of the current design. The nominal wear calculation indicates that over 840-kg will be processed before the keeper erodes to the cathode tube diameter. Given the modest difference in the parameters used for the nominal and “worst case” calculations and the assumptions that the single ions do not participate in the erosion, the magnitude of the difference in the two predictions erodes confidence in the accuracy of the results. The following sections seek to address the uncertainty in the erosion predictions quantitatively using probabilistic methods.

Effective Sputter Yield

In order to incorporate a Maxwellian ion distribution including both singly and doubly charged ions, the distribution function should be multiplied by the sputter yield and then integrated over velocity space. Incorporation of the angular dependence of the sputter yield further complicates the calculation. Fortunately for a low temperature ion population and a large plasma potential with respect to the keeper potential, ie $V_p \gg T_i$, the angular dependency of the sputter yield may be neglected for simplicity; the sputter yield for near normally incident ions differs from that of normally

incident ions by only a few percent typically.¹⁶ Again the sheath is assumed to be planar and parallel to the face of the keeper, and the effect of the keeper orifice has been neglected. In the present investigation, the mean ion angle of incidence with the keeper face was calculated to be between 5 and 15 degrees from normal incidence. A model was developed using a Monte Carlo approach to determine the effective sputter yield for a given ion population; this approach facilitates inclusion of an arbitrary sputter yield function. A random Maxwellian velocity distribution of ions was generated based on a given ion temperature. The ions with positive z velocity were accelerated through the plasma potential, and their energy at the keeper surface was calculated to compute the yield of each incident ion. To account for doubly charged ions, their yield was calculated by assuming that they fell through twice the field as the singly charged ions, and the yield for each incident ion was prorated by the likelihood it was either singly or doubly charged. The yields were summed over all of the ions in the distribution to calculate an effective sputter yield for the flux of ions to the surface.

$$Y_{eff} = \sum_i \left[\frac{N^+}{N^+ + N^{++}} Y(E_i^+) + \frac{N^{++}}{N^+ + N^{++}} Y(E_i^{++}) \right] \quad (3)$$

where N^+ and N^{++} are the number of singly and doubly charged ions, respectively, in the Monte Carlo simulation which strike the keeper. They are related to the ratio of double-to-single ion current by the following expressions:

$$R = \frac{j^{++}}{j^+} = \frac{2n^{++}}{n^+} \quad (4)$$

$$n^+ = \frac{J_k}{0.61e\sqrt{\frac{kT_e}{M}}} \frac{1}{1+R} \quad (5)$$

$$n^{++} = \frac{1}{2} \frac{J_k}{0.61e\sqrt{\frac{kT_e}{M}}} \frac{R}{1+R} \quad (6)$$

$$N^{++} = N^+ \frac{n^{++}}{n^+} \quad (7)$$

Similar inputs were put into the model as those used in the cold-ion approach to verify that the calculation was accurate. Although sophisticated Monte Carlo analyses typically require millions of particles, using four thousand ions was found to be sufficient for the calculations presented here.

Probabilistic Wear Analysis

The probabilistic wear analysis was conducted by using essentially the same physics as the deterministic model, but allowing the input parameters to vary over a range in order to assess the effect of the uncertainty in each parameter on the predicted wear. A log-normal distribution function was assumed for the ranges of ion temperature, electron temperature, plasma potential, sputtering threshold potential, the magnitude of the sputtering yield at 100-eV, and finally total the ion current to the keeper. The log-normal distribution function was chosen for numerical simplicity. The log-normal distribution function is defined as

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp\left[-\frac{1}{2\sigma^2} (\ln(x) - \mu)^2\right] \quad (8)$$

where σ and μ are the natural logarithms of the standard deviation and mean, respectively. Log-normal distribution functions with several values for σ are plotted in Figure 5 for reference in the discussion of the analysis. The general technique used to analyze the wear will work with any distribution function. The following section describes the logic behind the choices for the distributions used in this analysis and illustrates the ranges.

Parameter Distributions

Typically laser induced fluorescence (LIF) or heat flux probes are the experimental techniques used to measure ion temperature. To the authors' knowledge, only LIF has been used to examine the ion population within an ion thruster discharge chamber. Williams¹⁷ used LIF to measure the axial and radial velocities of singly ionized xenon in an ion thruster. From these data, he was able to discern that the ion population outside of the sheath was non-isotropic, and that it exhibited axial temperatures averaging approximately 0.75-eV and peaking to a little more than 1-eV for an NSTAR type discharge chamber.¹⁷ Difficulty arose in attempting to choose an ion temperature to use in the relatively simple model of the keeper erosion. As is discussed later, the plasma potential used was greater than that observed by either Williams¹⁷ or Foster and Patterson.¹⁰ To compensate for this, the ion temperature was chosen intuitively to more closely reflect the diffuse nature of the ion thruster discharge chamber plasma. Heating due to collisions with the energetic electrons is expected to raise the ion temperature only slightly relative to the temperature of ion thruster components. Consequently the ion temperature was taken to have a mean value of 0.2-eV. The deviations from the mean are those plotted in Figure 5 for all of the parameters. This results in a relatively small range of ion temperatures around the mean.

Although experimental techniques to measure plasma potential are well developed, few data have been published on the plasma potential within an ion engine discharge chamber during beam extraction.¹³ The results by Beattie and Matossian¹³ with a mercury ion engine indicated a plasma potential of up to 7-V above the discharge voltage during beam extraction. Several authors^{10,11} have recently measured plasma potential distributions in ion engine discharge chambers without beam extraction, finding that the plasma potential is generally between anode and cathode potentials. To be conservative, the plasma potential was set above the discharge voltage for both the deterministic and probabilistic cases. The mean plasma potential for the probabilistic analysis was set to 30-V, 6-V above the NEXT beginning of life discharge voltage. When assessing the effect of the uncertainty in plasma potential on the prediction of life, the mean plasma potential was set to 27-V to cover the spread of experiment data with and without beam extraction.

The ratio of double-to-single ion current to the keeper has yet to be measured accurately, and most analyses related to the NSTAR ion engine relied on the measurement from an ExB probe placed far downstream of the thruster.^{5,18} These data can be corrected for the conditions near the ion optics by modeling the charge exchange environment between the probe and the thruster. Correction for the environment near the keeper requires more rigor, including model development and validation. While additional experimentation and analytical investigation are necessary to quantify the ratio of double-to-single ion current on the keeper accurately, a conservative estimate would fix the ratio at or slightly above that measured downstream. Within the discharge chamber the electron current density, and consequently the ionization, is greatest near the cathode orifice, and intuitively the local density of doubly charged ions would be greater than or equal to the volume averaged value observed by a probe far downstream. Although some preliminary tests with the NEXT engine have indicated double-to-single ion current ratios in the plume of less than 0.10, the NSTAR peak power nominal maximum of 0.176 was chosen for a mean value to be conservative.

The total and distributed ion current to the keeper was measured in this investigation, and the error associated with the measurement was discussed previously. The keeper ion current for the full keeper was measured for varying discharge chamber efficiencies at constant beam current, and the resulting scatter is shown in

Figure 1. The standard deviation for the scatter is less than 2.5 percent for all beam currents. The magnitude of the keeper ion current and its distribution were taken from the experimental data reported in this paper.

The form of the sputter yield used in this investigation was described previously. Duchemin, *et al.*¹⁹ summarized sputtering yield data and theory near threshold, illustrating the uncertainty in sputter yields near threshold. A conservative approach was adopted for this investigation, using as the mean values the yield reported by Rosenberg and Wehner¹⁵ at 100-eV and the minimum threshold for sputtering molybdenum of 24-V reported by Stuart and Wehner.¹⁴ Given the spread in experimental data and analytical results compiled by Duchemin, *et al.*, the sputter yield appears to be nearly as uncertain at the ratio of double-to-single ion current to the keeper.

Analysis of NEXT Discharge Cathode Assembly

In order to calculate the probability density function for enlargement of the keeper orifice to the outer diameter of the cathode tube, a milestone in the erosion of the cathode assembly, a Monte Carlo approach was adopted for the parameters in Equations 1-3, 5, and 6. A log normal distribution was randomly generated using the mean values discussed in the previous section and the deviations illustrated in Figure 5. Although the results indicate some numerical noise, 12,000 iterations yielded convergence for the calculation.

The probability density function for keeper wear is plotted in Figure 6 for varying certainty in the ion temperature. Even with optimistic estimates of the certainties for all the parameters, the full-width at half-maximum (FWHM) is 48-kg. For variations in the ion temperature uncertainty ($\sigma=\ln(1.25)$), the FWHM climbs to 66-kg. The deviations for the calculated wear distributions are listed in Table 3, and the uncertainty in the ion temperature modestly impacts the uncertainty in the wear rate. The impact of the deviation in the ion temperature becomes more important as the mean value approaches the plasma potential.

The probability density function for keeper wear is plotted in Figure 7 for varying certainty in the plasma potential with respect to the keeper. The lower mean plasma potential used for this calculation resulted in an increase in the mean throughput of 245-kg for the case where all the parameters are known with a high degree of accuracy. Further, uncertainty in the plasma potential results in greater uncertainty in the wear of the keeper than all the other parameters in Equation 1, as

suggested by Figure 7 and quantified in Table 3. The distribution for the keeper wear when the uncertainty in plasma potential reached $\sigma=\ln(1.25)$ was poorly suited for curve fitting to the log-normal distribution.

The probability density function for keeper wear is plotted in Figure 8 for varying certainty in the ratio of double-to-single ion current at the keeper. For the maximum standard deviation in the ion current ratio, the FWHM was approximately 106-kg. Overall, the effect of uncertainty in the ion current ratio is less than other parameters as quantified in Table 3.

The probability density function for keeper wear is plotted in Figure 9 for varying certainty in the keeper ion current magnitude. While the effect of uncertainty in the ion current is significant, the keeper ion current as measured in this investigation, for a wide range of discharge conditions, exhibited a small standard deviation, comparable to $\sigma=\ln(1.10)$. The resultant uncertainty (one standard deviation) in the throughput calculation is then approximately 10 percent.

The probability density functions for keeper wear are plotted in Figure 10 and Figure 11 for varying certainty in the sputtering threshold and yield at 100-eV, respectively. Not surprisingly the threshold plays a strong role in determining the accuracy of the wear prediction. The effect of uncertainty in the sputtering threshold is comparable to that of the plasma potential. Uncertainty in the magnitude of the sputter yield effects the wear prediction in a manner comparable to the keeper ion current.

The accuracy of the probabilistic analysis presented here is inherently dependent upon the mean values and standard deviations listed in Table 2. The analysis technique enables quantification of the confidence in the prediction of the wear. Additionally, the results are useful in choosing where to focus experimental and analytical research. The results of this analysis indicate that evaluation of the plasma potential within the discharge chamber and refinement of the low energy sputter yield data are needed to reduce the uncertainty in predicting wear in the discharge chamber. Even if all of the parameters were well known, there is still a finite probability that the keeper wear will expose the orifice plate weld and the cathode heater to sputter erosion after 300-kg of throughput. In fact the uncertainty is likely greater than this optimistic prediction as discussed previously. The uncertainty analysis presented here also indicates that the variance observed in the keeper erosion during the NSTAR wear tests is expected.

CONCLUSIONS

An experimental investigation was conducted to measure the ion current distribution to the keeper in the NEXT ion engine. Keeper ion current measurements were taken over the throttling range of the engine with several different keeper orifice diameters. The keeper ion current scaled with the beam current, and the average keeper ion current density for the NEXT engine was the same as that of the NSTAR engine for the same average beam current density. The radial distribution of the keeper ion current density was also calculated from the experimental data and was highly peaked near the orifice.

The experimental data were used in a deterministic model to predict the wear of the keeper. The model yielded the keeper radius as a function of throughput and operating time. Under "worst case assumptions, the keeper orifice was predicted to erode to the cathode tube radius after processing 375-kg of xenon. This condition represents an intermediate condition necessary, but not sufficient, for several DCA failure modes. A rough estimate of the DCA life limit due to sputtering of approximately 844-kg was made based on the experience of the NSTAR ELT. The current design was found to exceed the qualification requirements.

Finally, a probabilistic wear assessment was performed to better understand the effect of uncertainties in the input parameters on the accuracy of the wear prediction. The predicted wear of the keeper appeared to be most sensitive to the plasma potential and the low-energy sputter yield. While the specific analysis performed indicated significant uncertainty in the wear rate of the discharge cathode keeper, the current understanding of the physics in the discharge chamber must be enhanced before the probabilistic technique can be used to predict wear with confidence. However, the deterministic approach cannot predict the confidence in the calculation. Consequently the ability to predict the lifetime of discharge chamber components is fundamentally tied to the accuracy with which the low-energy sputter yields and the plasma potential distribution are known. As the lifetime requirements for ion engines are increased dramatically over NSTAR for deep space missions, the ability to predict discharge chamber wear is becoming increasingly important.

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Table 1.—Deterministic Wear Calculation Parameters

Parameter	Nominal Wear Calculation	"Worst Case" Wear Calculation
J_B (A)	3.10	3.10
$R = j^{++}/j^{+}$	0.176	0.176
V_p (V)	25.0	30.0
V_{th} (V)	27.0	24.0
Y (100 eV)	0.06	0.06

Table 2.—Mean Values Used to Calculate the Distributions of the Keeper Erosion Throughput.

	T_i (eV)	T_e (eV)	V_p (V)	V_{th} (V)	j^{++}/j^+	$Y(100\text{ eV})$
Figure 6	0.2	4	30	24	0.176	0.06
Figure 7	0.2	4	27	24	0.176	0.06
Figure 8	0.2	4	30	24	0.176	0.06
Figure 9	0.2	4	30	24	0.176	0.06
Figure 10	0.2	4	30	24	0.176	0.06
Figure 11	0.2	4	30	24	0.176	0.06

Table 3.—Summary of the Log-Normal Distribution Deviations ($\exp(\sigma)$) for given Deviations in Individual Parameters. Refer to Equation 8 and Figure 6 to Figure 11.

Parameter \ Deviation	$\sigma = \ln(1.01)$	$\sigma = \ln(1.10)$	$\sigma = \ln(1.25)$
T_i	1.14	1.15	1.17
V_p	1.15	1.49	N/A
R	1.14	1.17	1.22
J_k	1.14	1.22	1.33
V_{th}	1.14	1.30	1.45
$Y(100\text{-eV})$	1.14	1.22	1.33

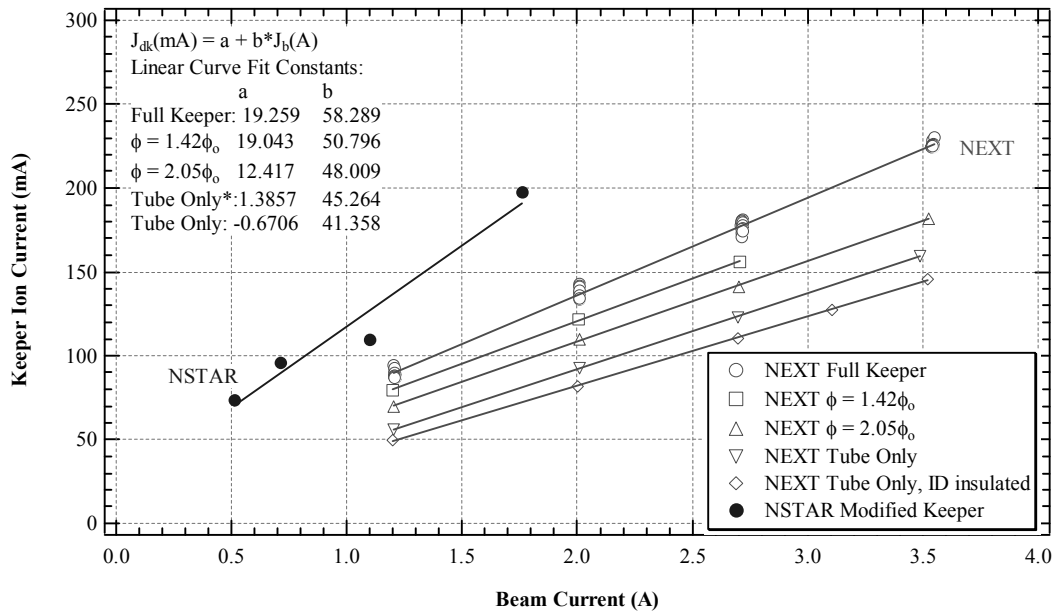


Figure 1 - Measured Ion Current to the Discharge Cathode Keeper for NEXT with Several Orifice Diameters and NSTAR.

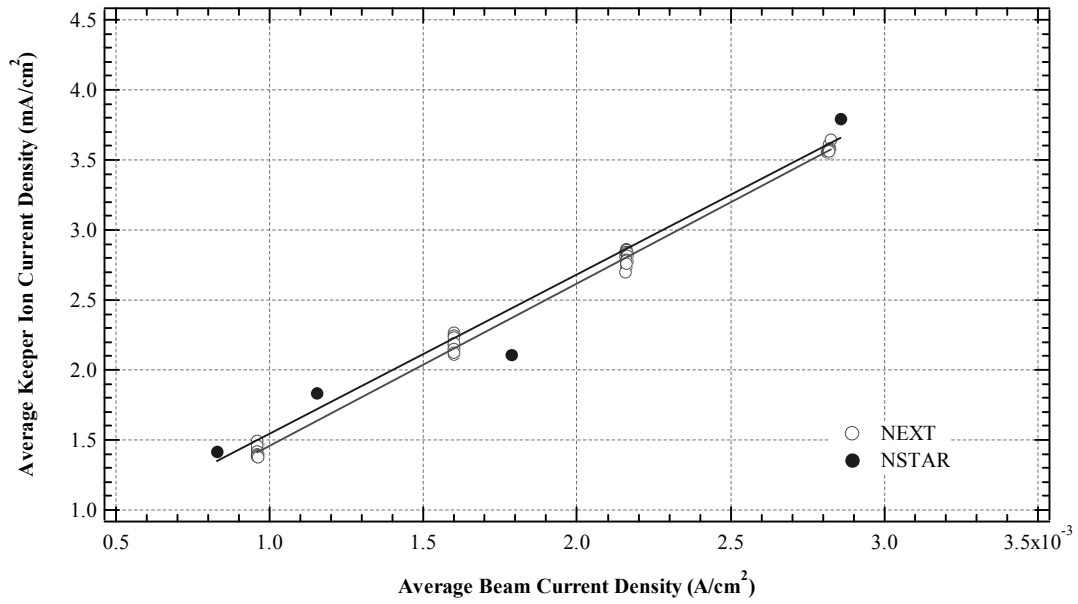


Figure 2 – The Area Averaged Ion Current Density for NEXT and NSTAR are Nearly Identical.

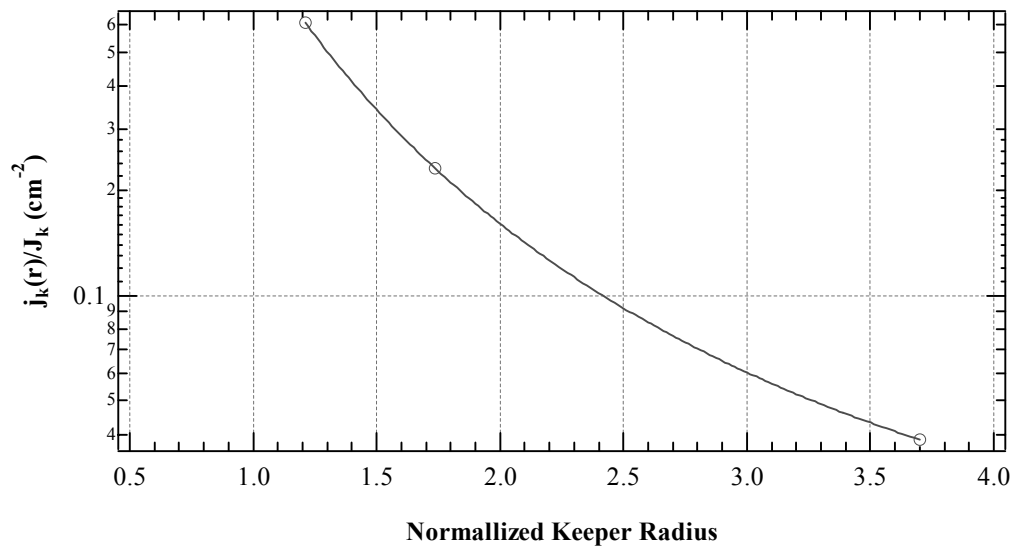


Figure 3 - Radial Distribution of Ion Current on the Face of the NEXT Discharge Cathode Keeper Calculated From the Data in Figure 1.

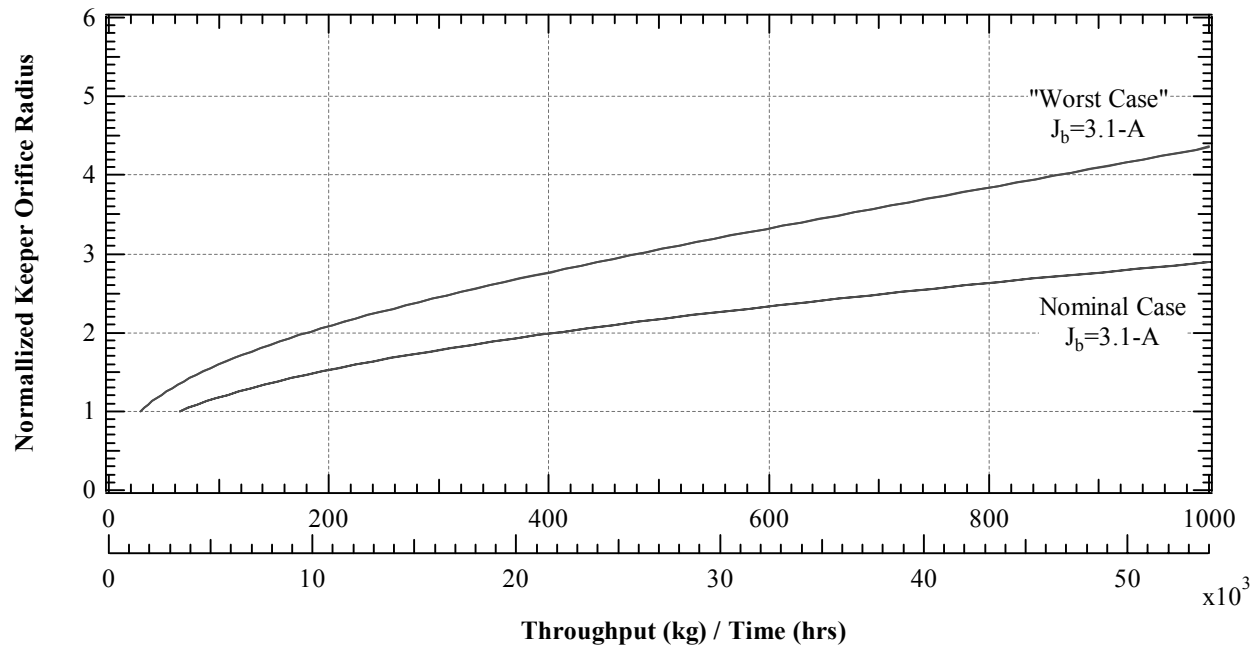


Figure 4 - Deterministic Predictions of the NEXT Discharge Cathode Keeper Wear Showing Greater than 405-kg (>20,000 hr at 3.1-A) Throughput Capability.

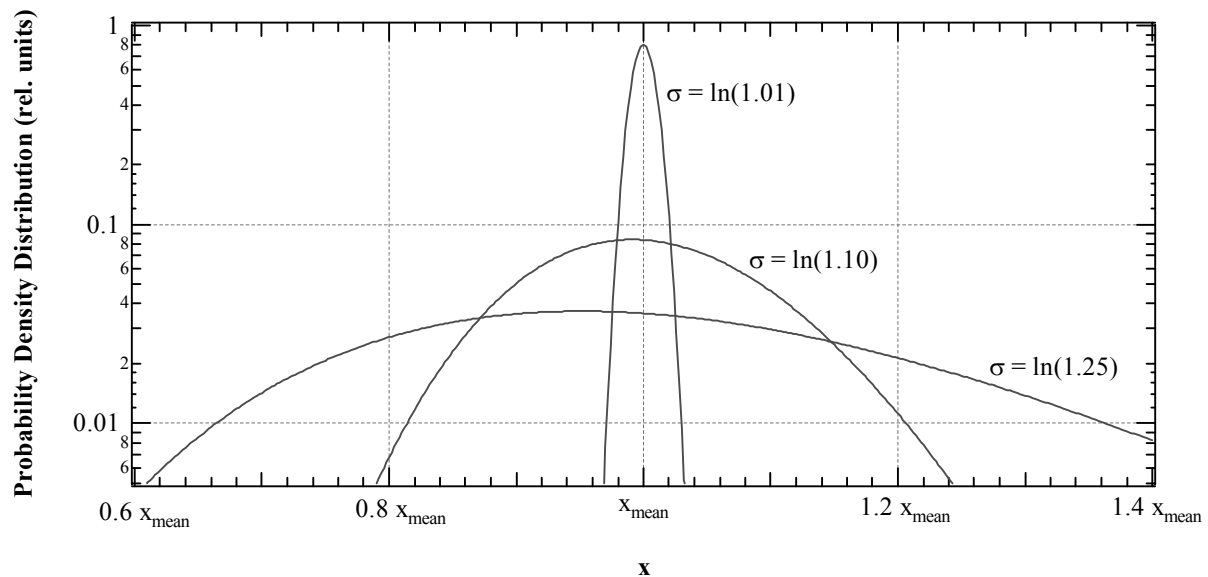


Figure 5 - Log Normal Probability Distributions Used for the Probabilistic Wear Analysis

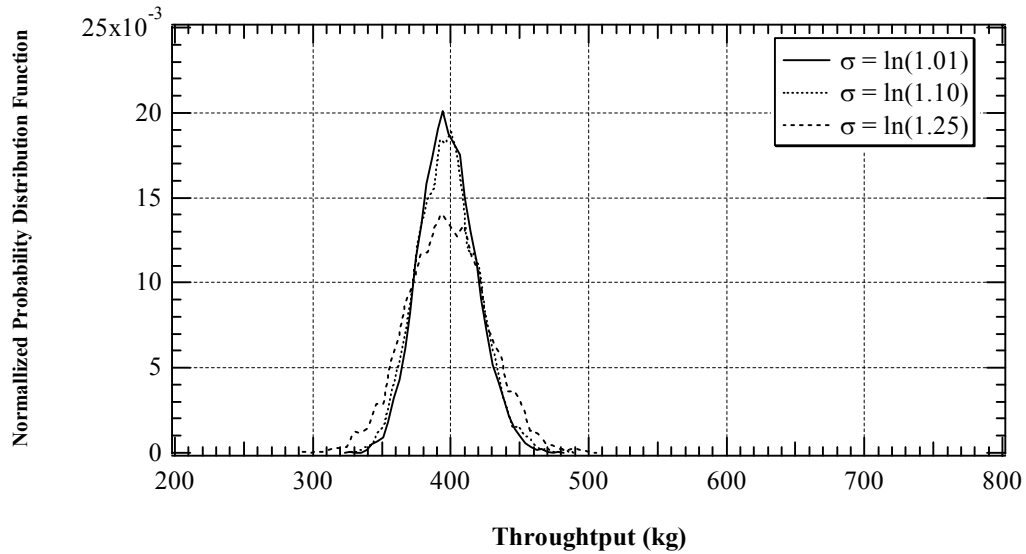


Figure 6 - Modest Variance in Xenon Throughput for Several Assumptions of Ion Temperature Uncertainty. (Throughput to Wear Keeper Orifice to Cathode Tube Diameter)

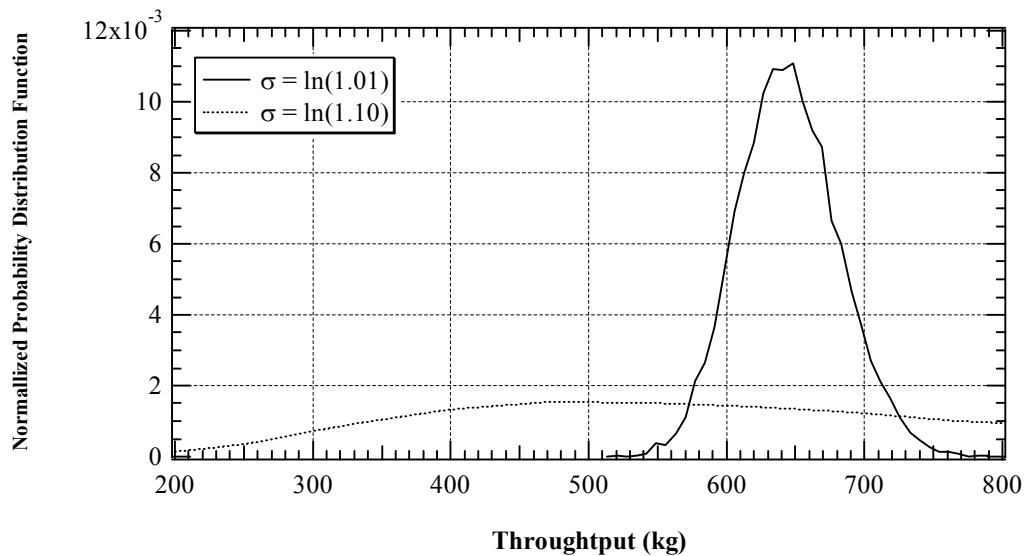


Figure 7 – Dependence of Probability Density Distribution of Xenon Throughput Capability on Plasma Potential Referenced to the Keeper. (Throughput to Wear Keeper Orifice to Cathode Tube Diameter, and Mean Plasma Potential of 24-V)

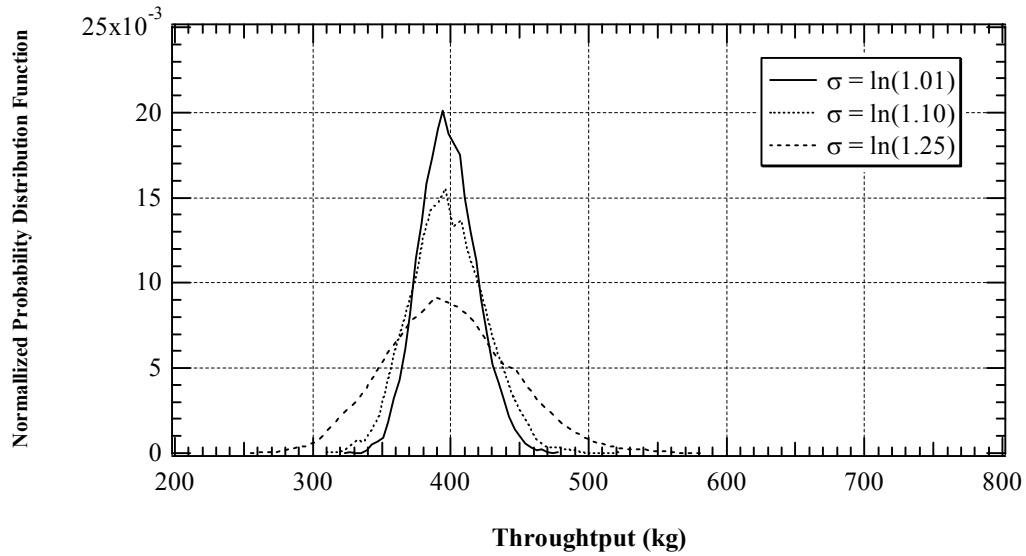


Figure 8 – Dependence of Probability Density Distribution of Xenon Throughput on the Certainty of the Ratio of Double-to-Single Ion Current to the Keeper. (Throughput at Keeper Wear to Cathode Tube Diameter)

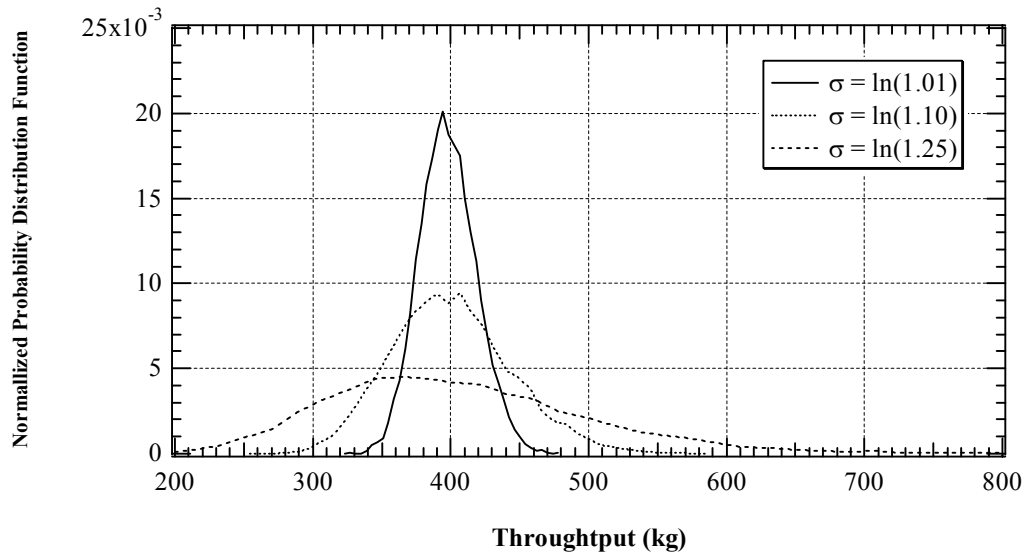


Figure 9 – Dependence of Probability Density Distribution of Xenon Throughput on the Keeper Ion Current Certainty. (Throughput at Keeper Wear to Cathode Tube Diameter)

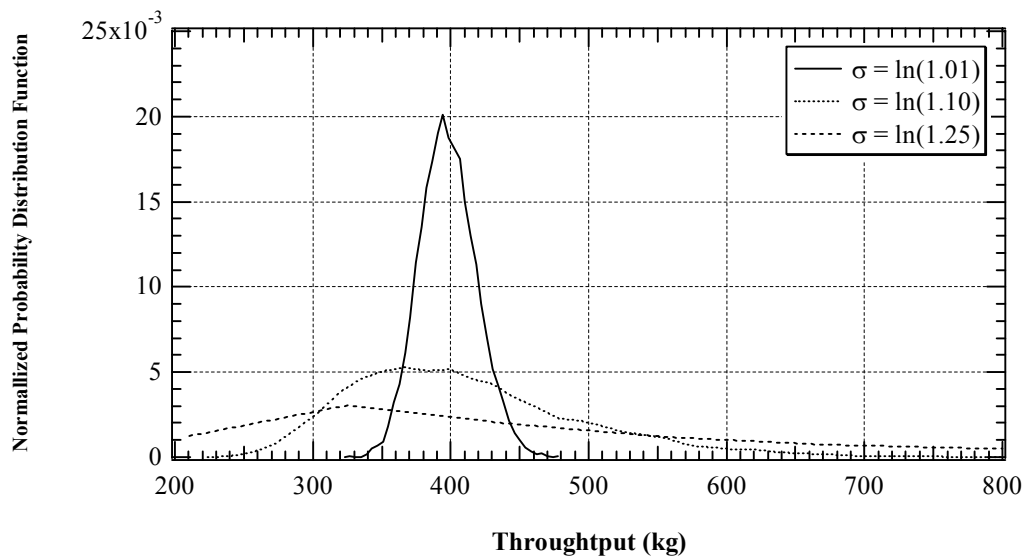


Figure 10 – Dependence of Probability Density Distribution of Xenon Throughput on the Uncertainty in the Sputtering Threshold Voltage. (Throughput at Keeper Wear to Cathode Tube Diameter)

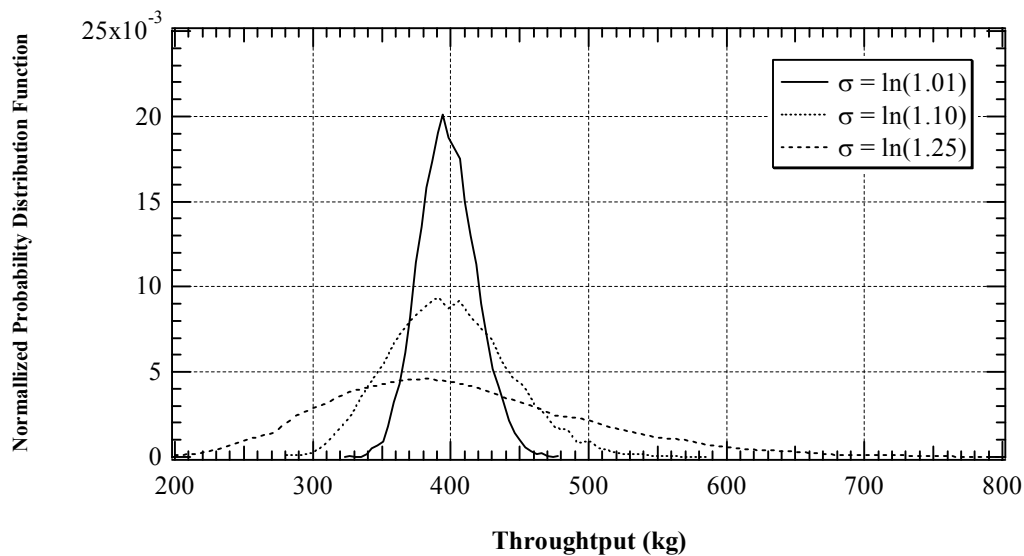


Figure 11 – Dependence of Probability Density Distribution of Xenon Throughput on the Uncertainty in the Sputter Yield at 100-eV. (Throughput at Keeper Wear to Cathode Tube Diameter)

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13. ABSTRACT (Maximum 200 words) Experimental and analytical investigations were conducted to predict the wear of the discharge cathode keeper in the NASA Evolutionary Xenon Thruster. The ion current to the keeper was found to be highly dependent upon the beam current, and the average beam current density was nearly identical to that of the NSTAR thruster for comparable beam current density. The ion current distribution was highly peaked toward the keeper orifice. A deterministic wear assessment predicted keeper orifice erosion to the same diameter as the cathode tube after processing 375 kg of xenon. A rough estimate of discharge cathode assembly life limit due to sputtering indicated that the current design exceeds the qualification goal of 405 kg. Probabilistic wear analysis showed that the plasma potential and the sputter yield contributed most to the uncertainty in the wear assessment. It was recommended that fundamental experimental and modeling efforts focus on accurately describing the plasma potential and the sputtering yield.				
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